



# Searches for lepton flavour and lepton number violation in $K^+$ decays

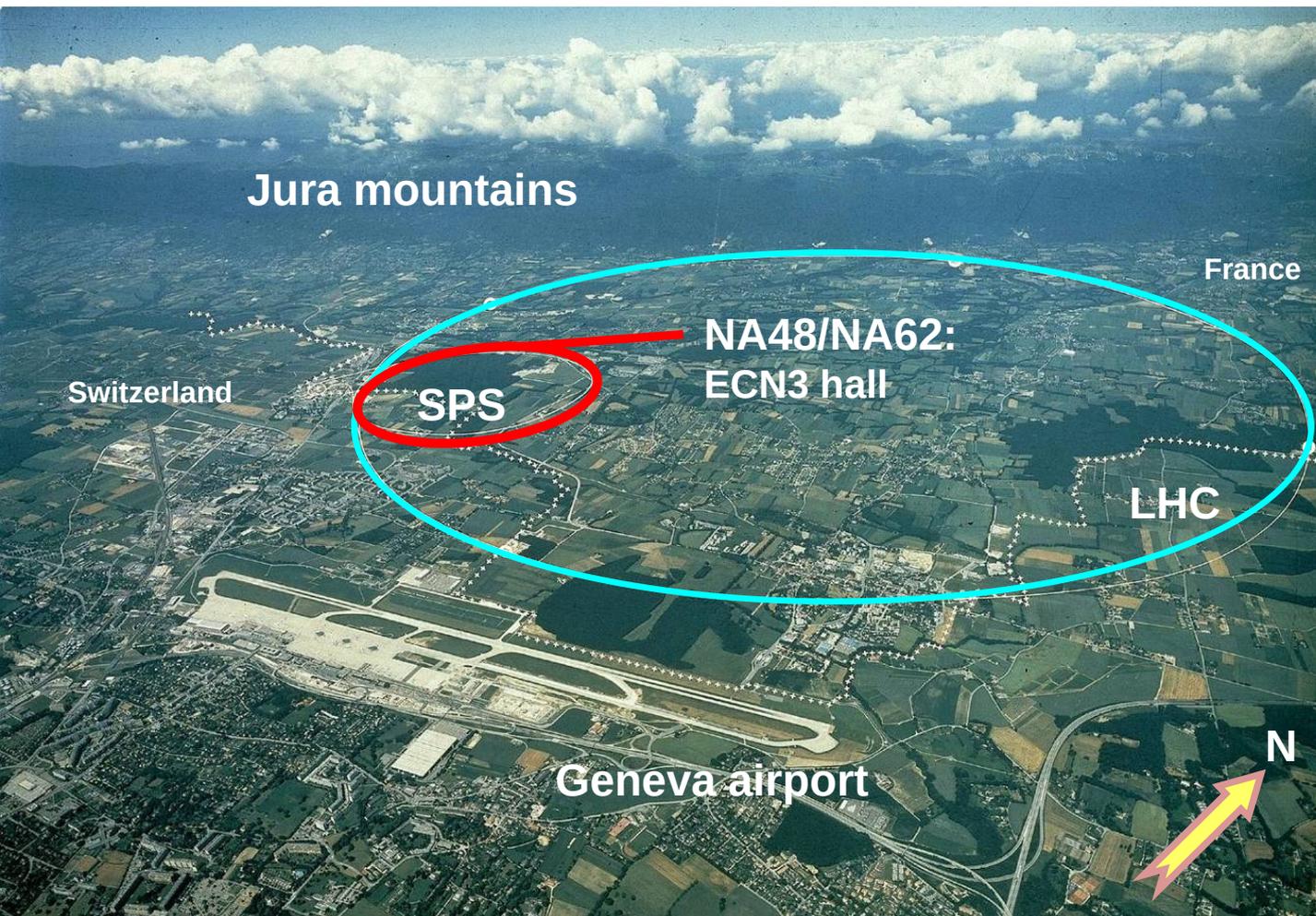
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on behalf of the CERN-NA62 collaboration

The 21<sup>st</sup> International Workshop on Neutrinos from Accelerators (NUFACT2019),  
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# NA62 experiment at CERN



**NA62 experiment** is located at north area(NA) of CERN.

**Protons** are extracted from **SPS** with  $p = 400 \text{ GeV}/c$  producing a secondary beam of hadrons ( $\sim 6\%$  are kaons).

**Kaon decay in-flight technique.**

## NA62 Timeline

Dec 2008: NA 62 Approval  
2009 – 2014: Detector R&D, Installation

2015: Commissioning

2016 – 2017 – 2018: Physics Runs

2021 – 2023: Next Physics Runs



Currently  $\sim 200$  participants from 31 institutes

# NA62 experiment at CERN

**Main goal** is to measure the  $\mathbf{K^+ \rightarrow \pi^+\nu\bar{\nu}}$  branching fraction with 10% precision.

**First  $\pi\nu\bar{\nu}$  result:** [PLB 791 (2019) 156]

**Broader physics programme:** [SPSC NA62 (2018)]

## Standard kaon physics

- Branching fraction measurements of all main  $K^+$  decay modes
- $\chi_{PT}$ :  $K^+ \rightarrow \pi^+\gamma\gamma$ ,  $K^+ \rightarrow \pi^+\pi^0e^+e^-$
- Lepton universality:  $R_K = \Gamma(K^+ \rightarrow e^+\nu_e)/\Gamma(K^+ \rightarrow \mu^+\nu_\mu)$

## Rare and forbidden $K^+$ and $\pi^0$ decays

- $K^+$  physics:  $K^+ \rightarrow \pi^+l^+l^+$ ,  $K^+ \rightarrow \pi^+\gamma l^+l^+$ ,  $K^+ \rightarrow l^+\nu\gamma$ , [ $l = e, \mu$ ]
- **LNV/LFV searches:**  $K^+ \rightarrow \pi^+\mu^\pm e^\pm$ ,  $K^+ \rightarrow \pi^-\mu^+e^+$ ,  $\mathbf{K^+ \rightarrow \pi^-l^+l^+}$  [ $l = e, \mu$ ]
- $\pi^0$  physics:  $K^+ \rightarrow \pi^+\pi^0$ ,  $\pi^0 \rightarrow e^+e^-$ ,  $\pi^0 \rightarrow e^+e^-e^+e^-$ ,  $\pi^0 \rightarrow \gamma\gamma(\gamma)$

**This talk**

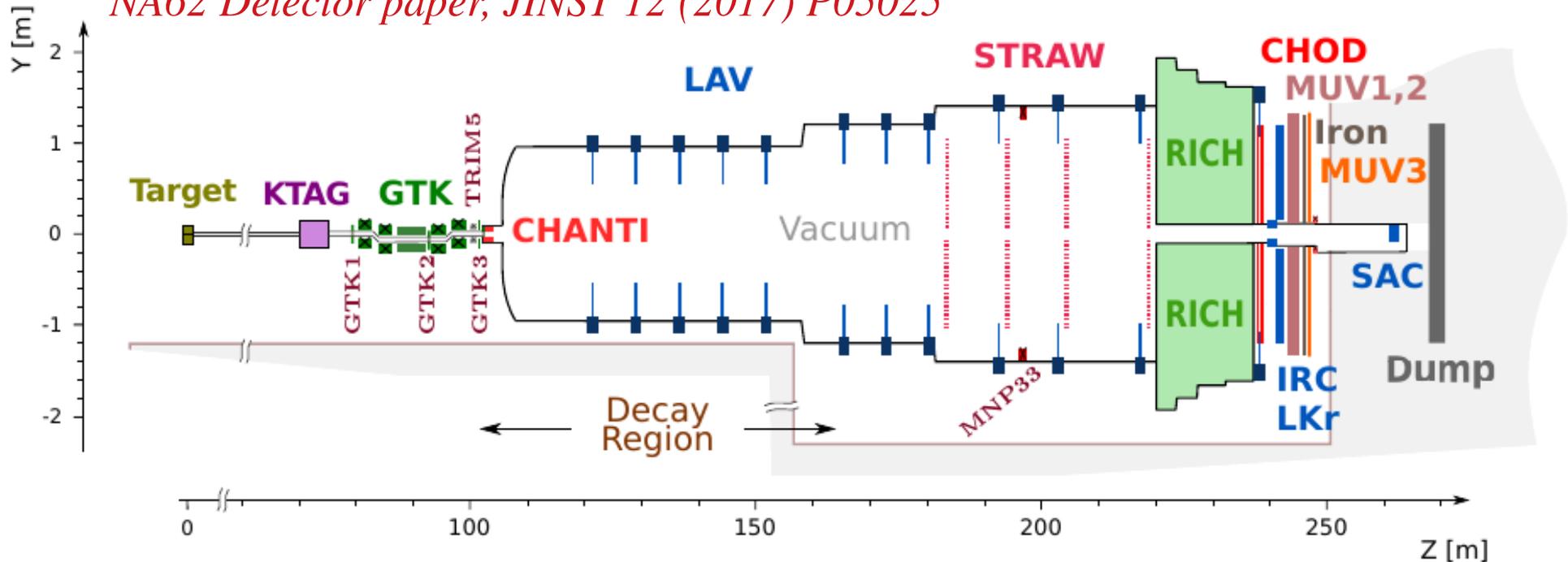


## Exotics searches (talk by Mathieu Perrin-Terrin @ Exotics at NA62 )

- Heavy Neutral Lepton (HNL) production:  $K^+ \rightarrow l^+\nu_h$
- Dark photon ( $A'$ ):  $K^+ \rightarrow \pi^+\pi^0$ ,  $\pi^0 \rightarrow A'\gamma$ ,  $A' \rightarrow$  invisible

# The NA62 detector

*NA62 Detector paper, JINST 12 (2017) P05025*



## Secondary beam

- Momentum **75 GeV/c**
- Composition: **K<sup>+</sup>(6%)**,  $\pi^+$ (70%), p(24%)
- Nominal beam rate: 750 MHz
- K<sup>+</sup> rate 45 MHz;
- ~5 MHz K<sup>+</sup> decays in fiducial volume

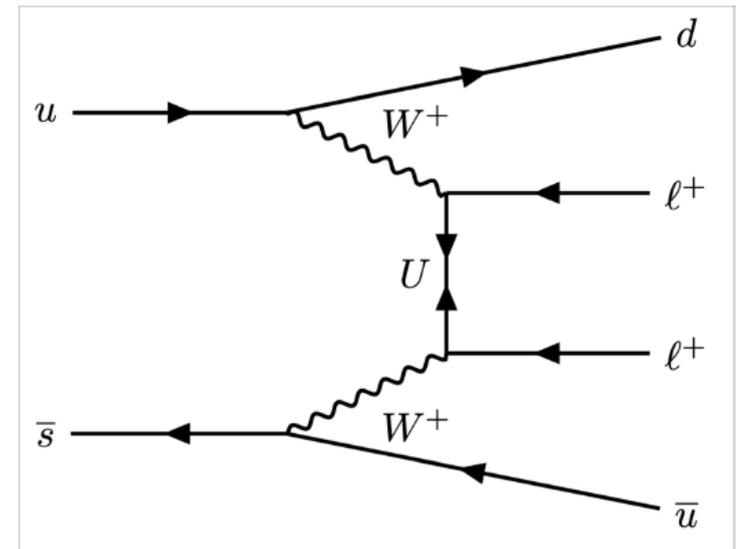
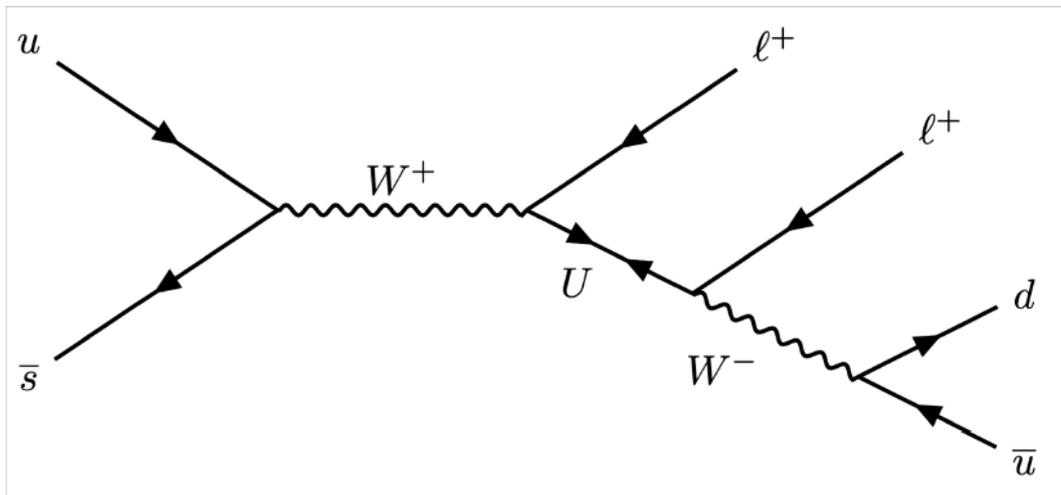
- **STRAW** spectrometer: downstream 3 track reconstruction
- **KTAG** (K<sup>+</sup>), **RICH** ( $\pi/\mu/e$  separation): PID with Cherenkov detectors
- **LKr** ( $\pi/\mu/e$  separation): PID via E/p
- **LAV**, **LKr**, **SAV**: photon veto
- **MUV3**: muon ID/veto

# Searches for lepton flavour and lepton number violation

*First result based on the 30% 2016-2018 data:*

*Phys. Lett. B 797 (2019) 134794*

# LFV/LNV $K^+ \rightarrow \pi^- l^+ l^+$



## Violation of lepton flavour/number conservation laws predicted in BSM models:

- $K^+ \rightarrow \pi^- l^+ l^+$ :  $\Delta L = 2$  and  $\Delta L_\mu = 2$  or  $\Delta L_e = 2$  ( $l = \mu$  or  $e$ ): via Majorana neutrinos  
U [JHEP 0905 (2009) 030], [PL B491(2000)285-290]

## Experimental Status (results at 90% C.L):

- $\text{Br}(K^+ \rightarrow \pi^- e^+ e^+) < 6.4 \times 10^{-10}$  [BNL E865: PRL 85(2000)2877]
- $\text{Br}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 8.6 \times 10^{-11}$  [CERN NA48/2: PL B769(2017)67]

# LFV/LNV Searches at NA62

- Search in 3 months of continuous data taking July-October 2017
- Blind analysis strategy
- Dedicated trigger lines: multi-track final states with  $e^\pm$  or  $\mu^\pm$

Trigger name	Requirements	Data Samples
Di-Muon	3 tracks, 2 muon candidates	Collect SM $K^+ \rightarrow \pi^+\mu^+\mu^-$ & LNV $K^+ \rightarrow \pi\mu^+\mu^+$
Multi-track e	3 track, 20 GeV deposit in LKr	Collect SM $K^+ \rightarrow \pi^+e^+e^-$ & LNV $K^+ \rightarrow \pi e^+e^+$
Multi-track	3 tracks, minimum bias	Control samples for background studies

## Corresponding SM channels used for normalization

- Common event selection (differs mostly by charge)
- Main systematic uncertainties cancel (trigger/ detector efficiency/pileup)

$$\text{Br}(K^+ \rightarrow \pi^+e^+e^-) = (3.00 \pm 0.009) \times 10^{-7} \text{ [PL B677(2009)246]}$$

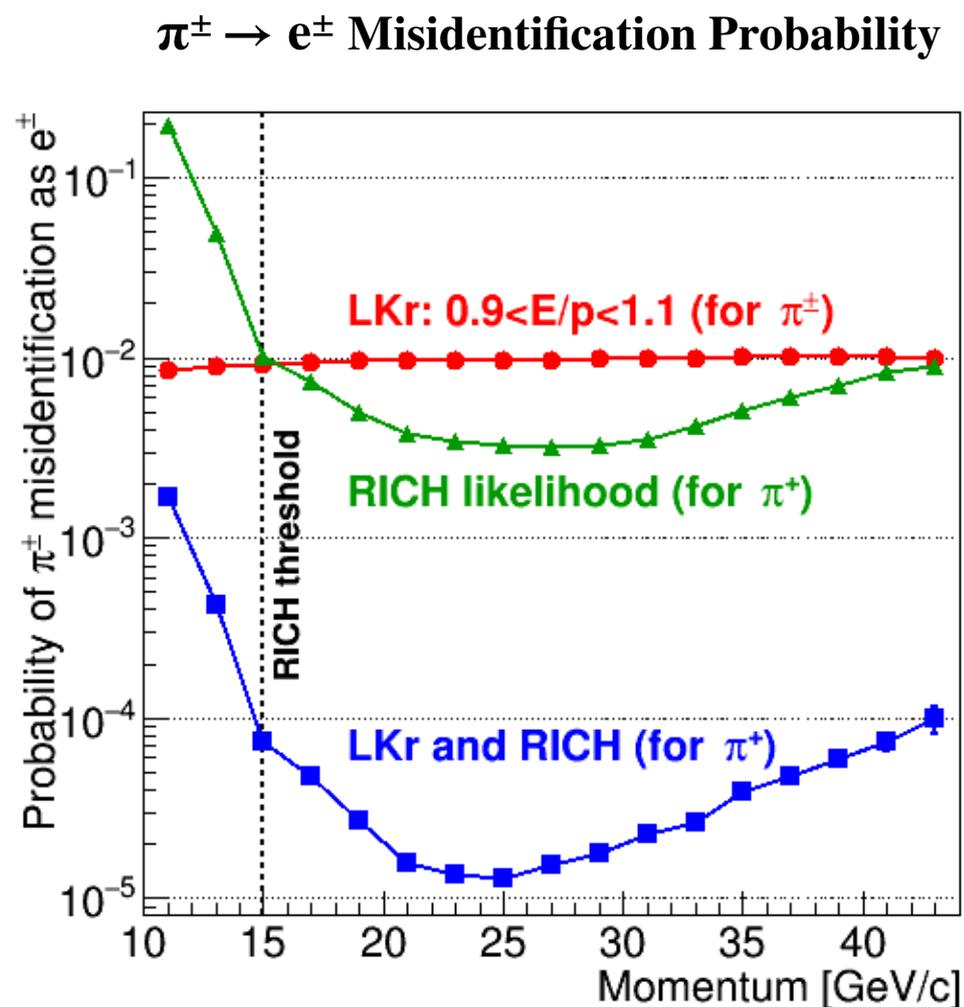
$$\text{Br}(K^+ \rightarrow \pi^+\mu^+\mu^-) = (0.962 \pm 0.025) \times 10^{-7} \text{ [PL B697(2011)107]}$$

# Backgrounds and PID

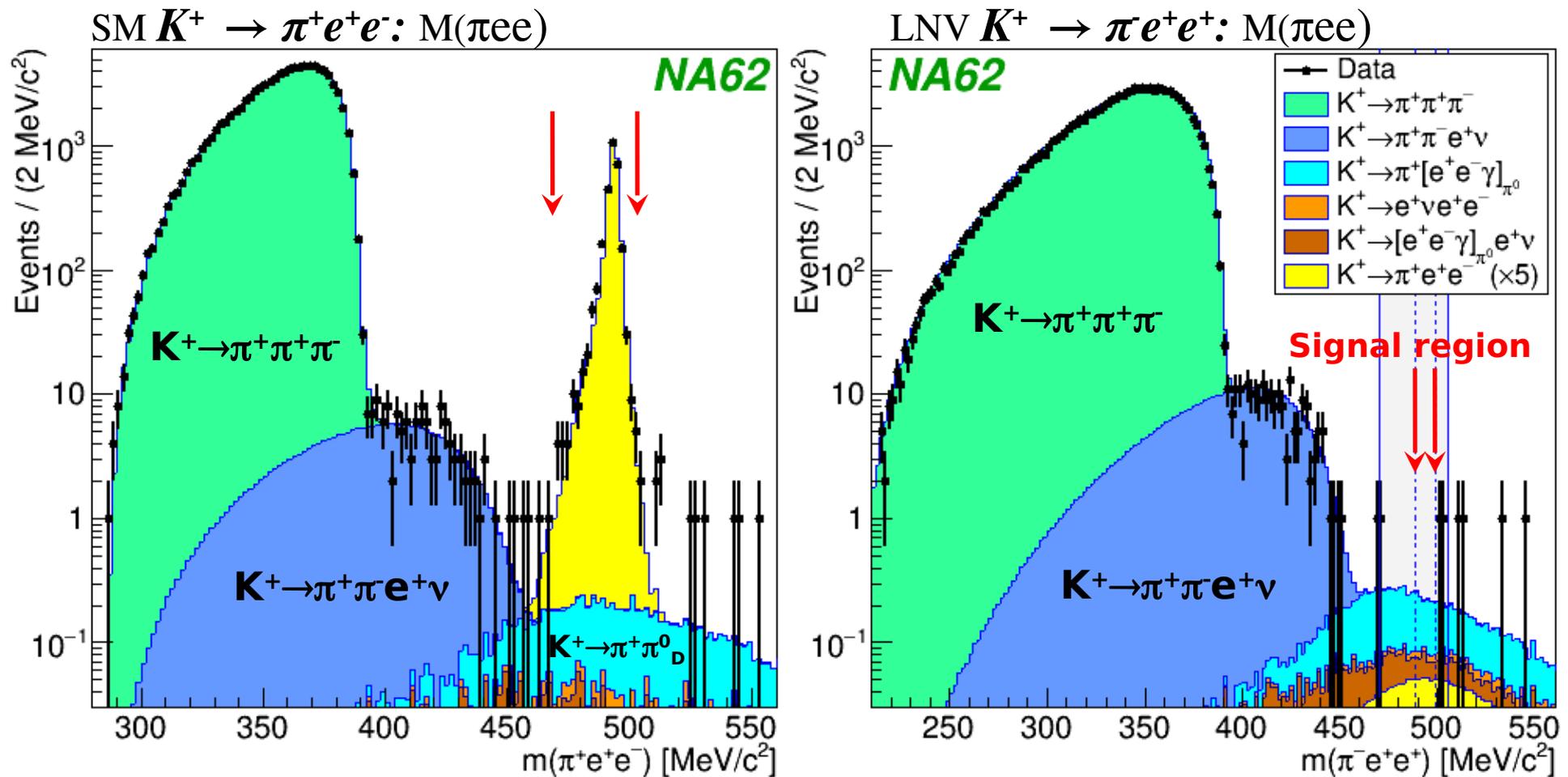
- Major background for 3-track decays: the  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  decay (**BR=5.6%**).

## Background mechanisms:

- Single/double misidentification:  
 $\pi^\pm \rightarrow e^\pm$ ,  $\pi^\pm \rightarrow \mu^\pm$
- Pion decay in flight (9% probability):  
 $\pi^\pm \rightarrow \mu^\pm$  (99.9%),  $\pi^\pm \rightarrow e^\pm$  ( $1.2 \times 10^{-4}$ )
- Studied with data-driven methods and dedicated simulations
- Pion/electron identification:
  - 1) by energy deposit in LKr (**E/p**);
  - 2) by the RICH signal pattern.

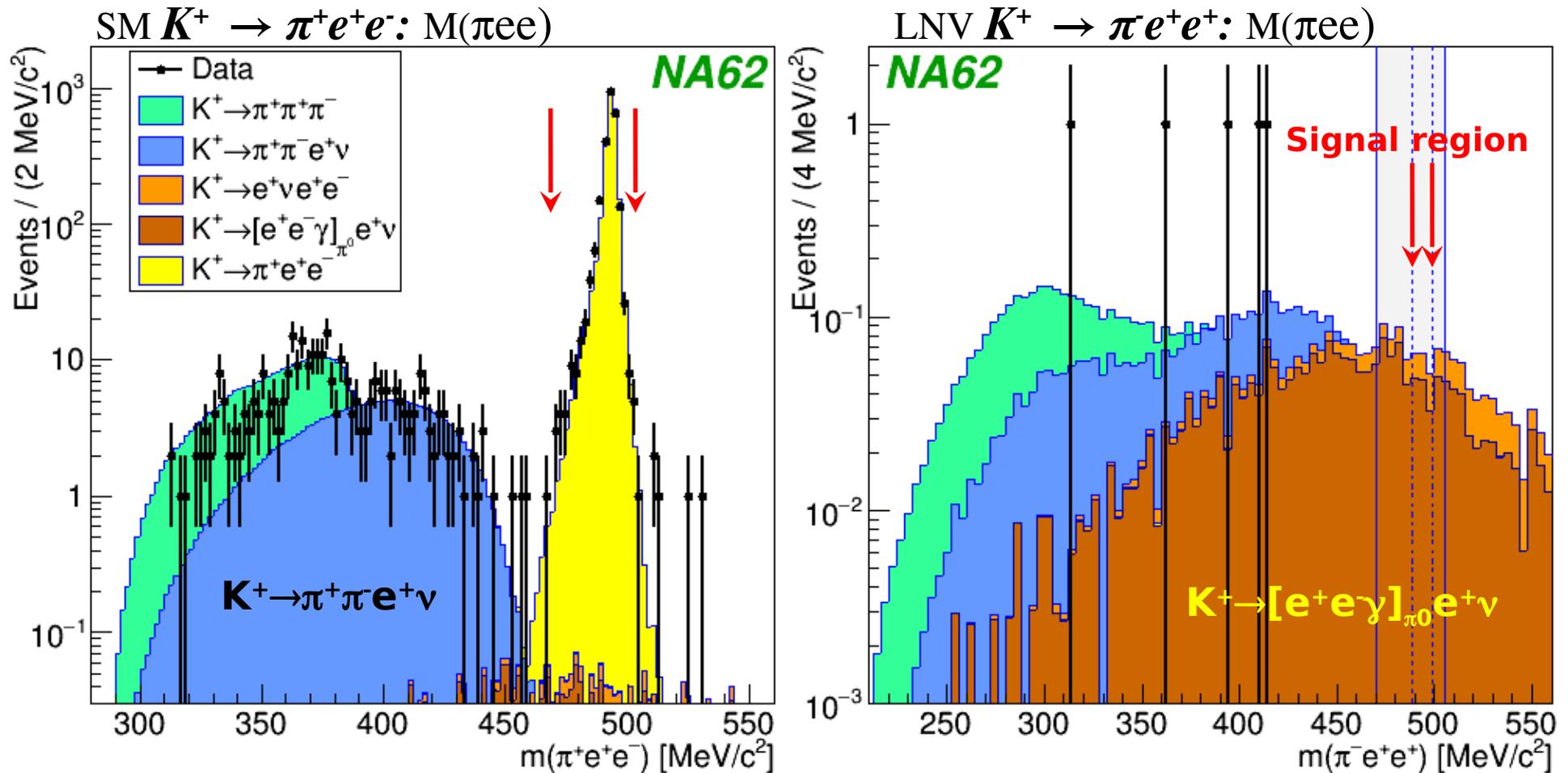


# $K^+ \rightarrow \pi^- e^+ e^+$ : auxiliary selection



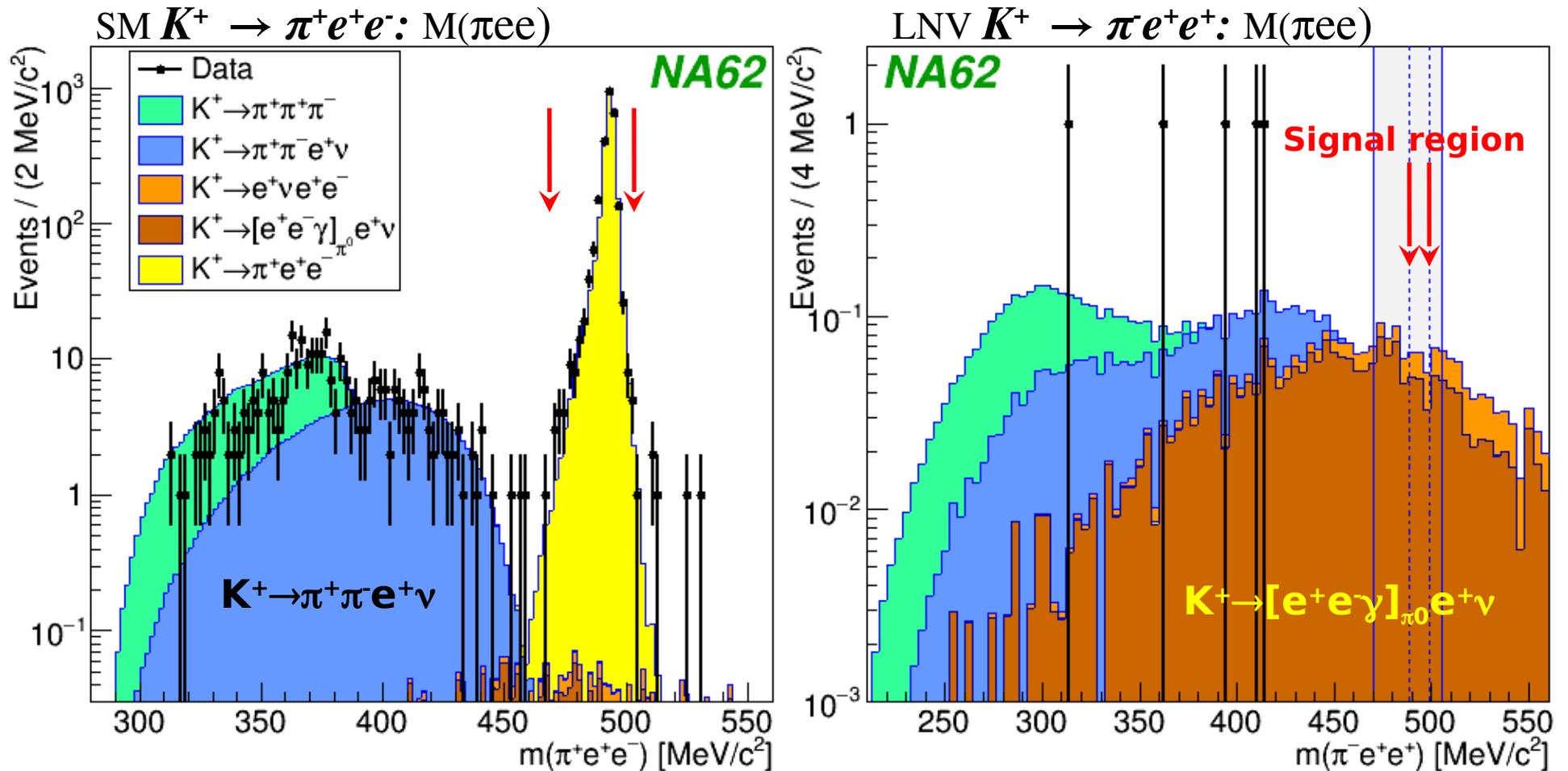
- Auxiliary: LKr only used for pion/electron ID
- Validation of background estimates in control mass regions
- LNV sensitivity limited by  $K^+ \rightarrow \pi^+ [e^+ e^- \gamma]_{\pi^0}$  background

# $K^+ \rightarrow \pi^- e^+ e^+$ : main selection



- **Standard: LKr + RICH used for pion/electron ID**
- About 10% loss of SES, ~ 6 times lower background
- **Better discovery potential for LNV**

# $K^+ \rightarrow \pi^- e^+ e^+$ : normalization



- **2484** SM  $K^+ \rightarrow \pi^+ e^+ e^-$  observed candidates
- **BR** ( $K^+ \rightarrow \pi^+ e^+ e^-$ ) =  **$(3.00 \pm 0.09) \times 10^{-7}$**
- $K^+$  decays in FV:  $N_K = (2.14 \pm 0.07) \times 10^{11}$

# $K^+ \rightarrow \pi^- e^+ e^+$ : results

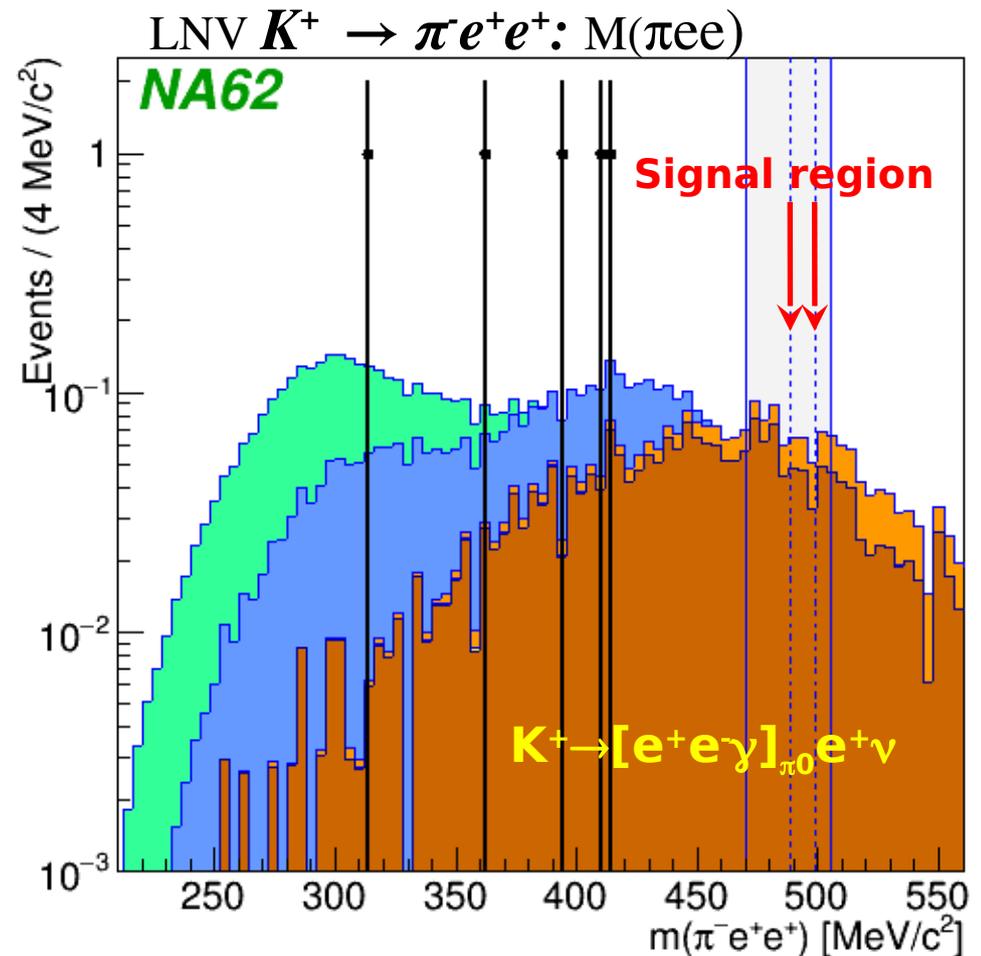
$$N_K = (2.14 \pm 0.07) \times 10^{11}$$

Signal Acceptance: **4.98%**

$$\text{SES} = (0.94 \pm 0.03) \times 10^{-10}$$

Expected background:  **$0.16 \pm 0.03$  evt**

Candidates observed: **0**



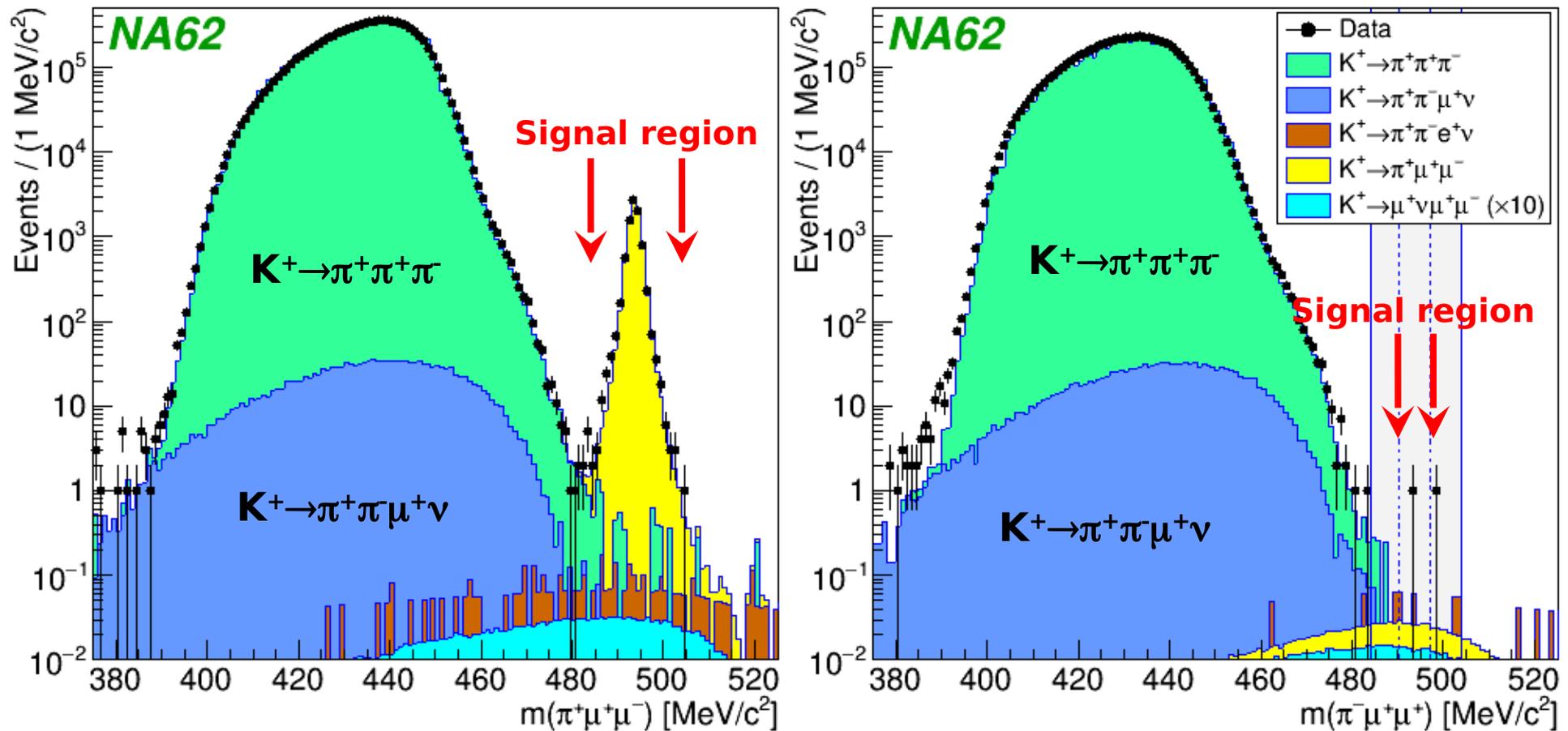
Set upper limit on BR using CLs statistical treatment:

$$\text{BR}(K^+ \rightarrow \pi^- e^+ e^+) < 2.2 \times 10^{-10} \text{ at } 90\% \text{ CL}$$

# Search for $K^+ \rightarrow \pi^- \mu^+ \mu^+$ decay

SM  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ :  $M(\pi\mu\mu)$

LNV  $K^+ \rightarrow \pi \mu^+ \mu^+$ :  $M(\pi\mu\mu)$

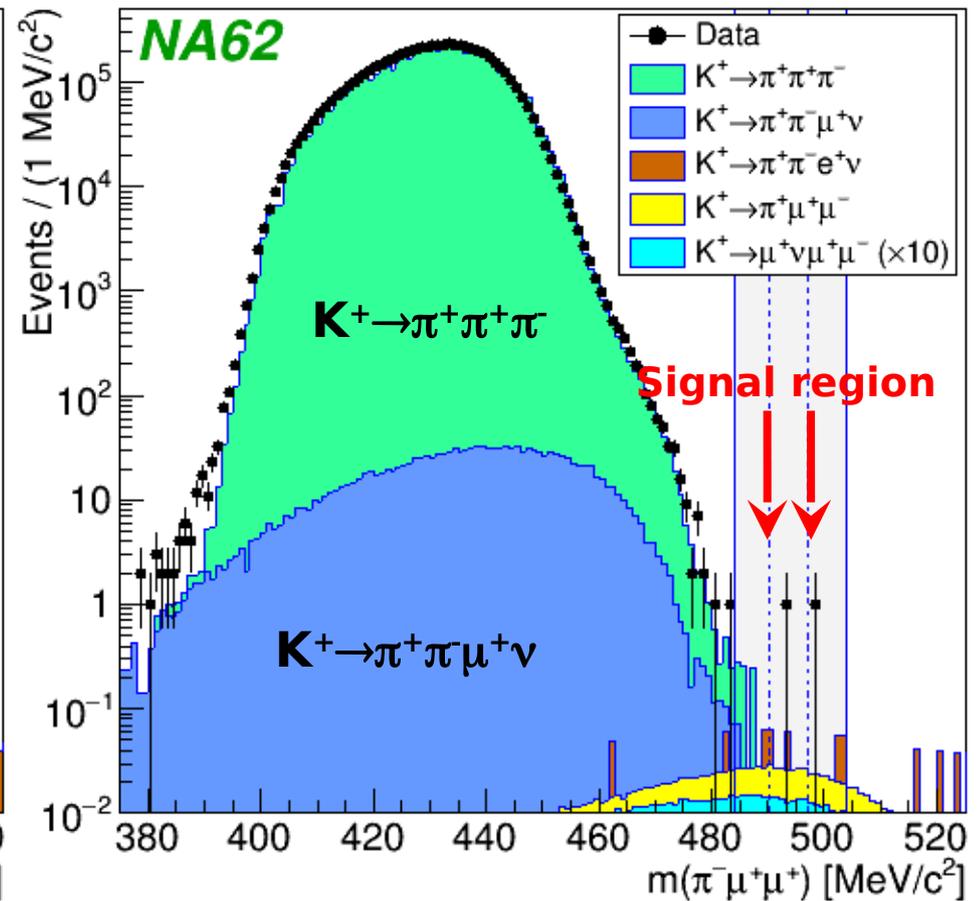
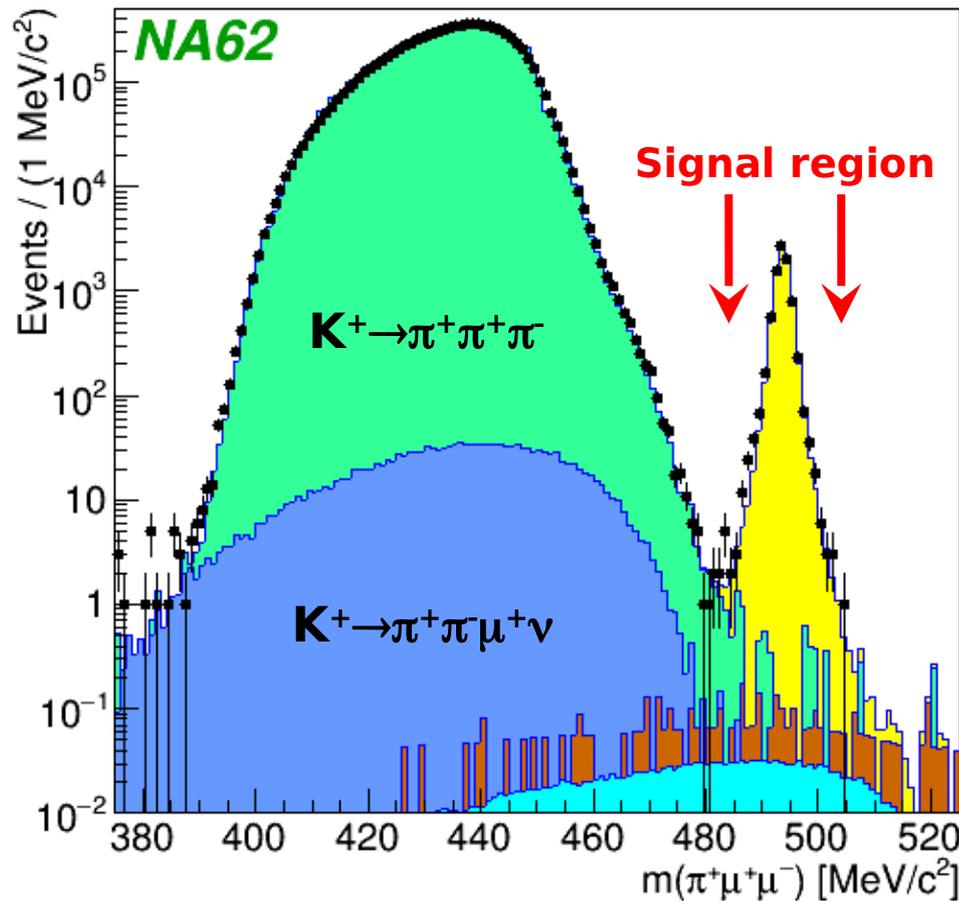


- **Standard: LKr + MUV3 used for pion/muon ID**
- Background in SM signal mass region: 0.07%
- Background to LNV due to pion in-flight decays and  $\pi^\pm \rightarrow \mu^\pm$  misidentification

# $K^+ \rightarrow \pi^- \mu^+ \mu^+$ : normalization

SM  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ :  $M(\pi\mu\mu)$

LNV  $K^+ \rightarrow \pi \mu^+ \mu^+$ :  $M(\pi\mu\mu)$



8357 observed candidates

$$\text{BR}(K^+ \rightarrow \pi^+ \mu^+ \mu^-) = (0.962 \pm 0.025) \times 10^{-7}$$

$$K^+ \text{ decays in FV: } N_K = (7.94 \pm 0.23) \times 10^{11}$$

# $K^+ \rightarrow \pi^- \mu^+ \mu^+$ : results

$$N_K = (7.94 \pm 0.23) \times 10^{11}$$

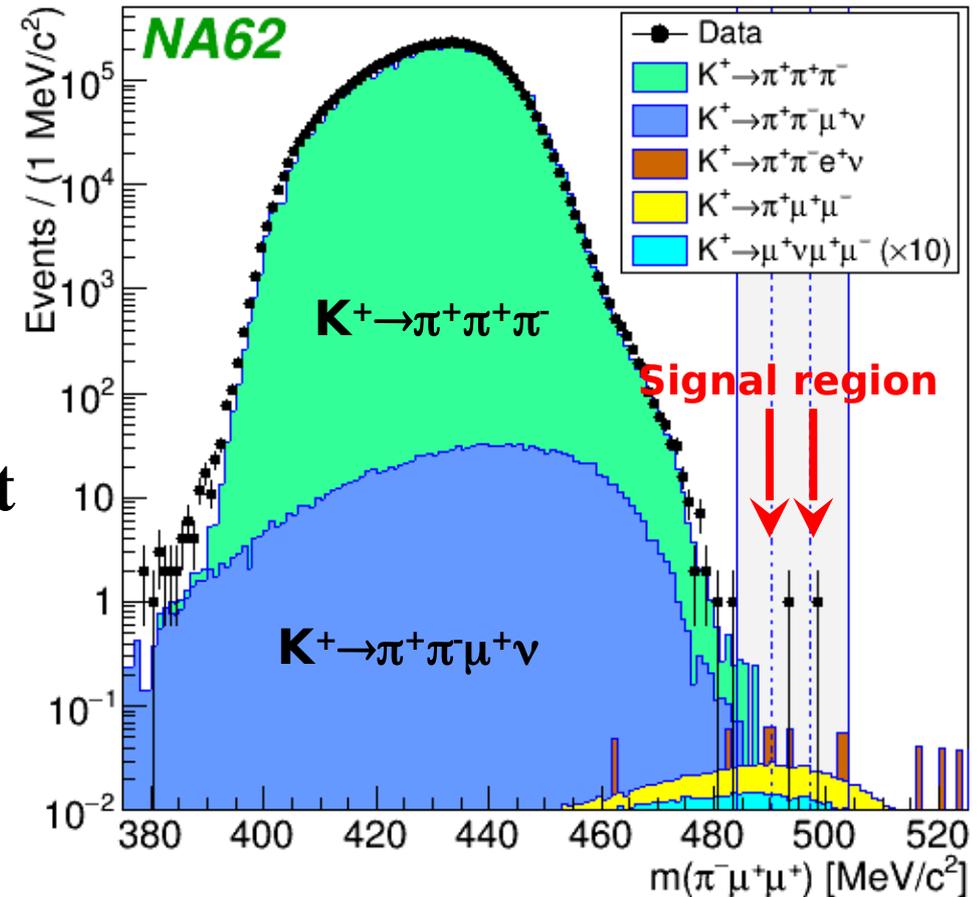
Signal Acceptance: **9.81%**

$$SES = (1.28 \pm 0.04) \times 10^{-11}$$

Expected background:  **$0.91 \pm 0.41$  evt**

Candidates observed: **1**

LNV  $K^+ \rightarrow \pi \mu^+ \mu^+$ :  $M(\pi \mu \mu)$



Set upper limit on BR using CLs statistical treatment:

$$\text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \text{ at } 90\% \text{ CL}$$

# LFV/LNV: results and prospects

Six analyses are in progress, none is limited by background

Set upper limits on BR using CLs statistical treatment:

$$\text{BR}(\mathbf{K}^+ \rightarrow \boldsymbol{\pi} \mathbf{e}^+ \mathbf{e}^+) < 2.2 \times 10^{-10} \text{ at } 90\% \text{ CL}$$

*Phys. Lett. B 797 (2019) 134794*

$$\text{BR}(\mathbf{K}^+ \rightarrow \boldsymbol{\pi} \boldsymbol{\mu}^+ \boldsymbol{\mu}^+) < 4.2 \times 10^{-11} \text{ at } 90\% \text{ CL}$$

Factor 2-3 improvement over previous results [NA48/2 and BNL-E865]

For  $\mathbf{K}^+ \rightarrow \boldsymbol{\pi} \boldsymbol{\mu}^+ \mathbf{e}^+$  [LNV] and  $\mathbf{K}^+ \rightarrow \boldsymbol{\pi}^+ \boldsymbol{\mu}^- \mathbf{e}^+$  [LFV]

**SES**  $\approx 5 \times 10^{-11}$  (factor  $\sim 5$  improvement on BNL-E865)

For  $\mathbf{K}^+ \rightarrow \mathbf{e}^+ \nu \boldsymbol{\mu}^+ \boldsymbol{\mu}^+$  [LFV], **SES**  $\approx 5 \times 10^{-11}$

(the first search for this mode);

For  $\mathbf{K}^+ \rightarrow \boldsymbol{\mu}^- \nu \mathbf{e}^+ \mathbf{e}^+$  [LFV], **SES**  $\approx 1 \times 10^{-10}$

(factor **100** improvement on PDG).

The full **2016 18** dataset is  $\sim 3$  times the size of **2017** dataset.

Not competitive yet for  $\mathbf{K}^+ \rightarrow \boldsymbol{\pi}^+ \boldsymbol{\mu}^+ \mathbf{e}^-$  and  $\boldsymbol{\pi}^0 \rightarrow \boldsymbol{\mu}^\pm \mathbf{e}^\mp$ .

# Spares

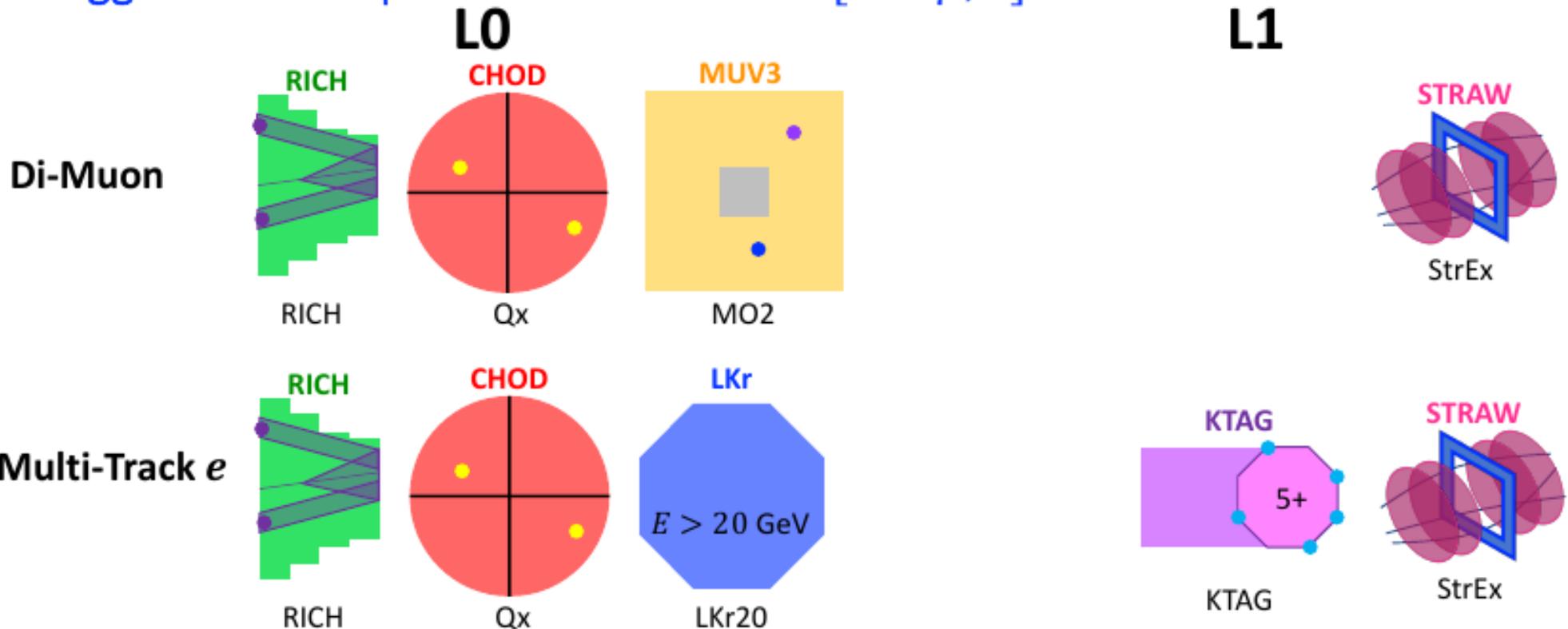
# LNV/LFV : Previous Experimental Results

## 3-track decays with closed Kinematics

Decay	LNV/LFV ?	BR Upper Limit (@90% CL)	Experiment	Publication
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	LNV & LFV	$8.6 \times 10^{-11}$	NA48/2	<a href="#">PL B769 67 (2017)</a>
$K^+ \rightarrow \pi^- e^+ e^+$	LNV & LFV	$6.4 \times 10^{-10}$	BNL E865	<a href="#">PRL 85 2877 (2000)</a>
$K^+ \rightarrow \pi^- \mu^+ e^+$	LNV & LFV	$5.0 \times 10^{-10}$	BNL E865	<a href="#">PRL 85 2877 (2000)</a>
$K^+ \rightarrow \pi^+ \mu^- e^+$	LFV	$5.2 \times 10^{-10}$	BNL E865	<a href="#">PRL 85 2877 (2000)</a>
$K^+ \rightarrow \pi^+ \mu^+ e^-$	LFV	$1.3 \times 10^{-11}$	BNL (E777+)E865	<a href="#">PR D72 012005 (2005)</a>

- NA62 already competitive for these decays except  $K^+ \rightarrow \pi^+ \mu^+ e^-$  (focus of E865 experiment).

# Trigger Chain Graphics : $K^+ \rightarrow \pi^- \ell^+ \ell^+$ [ $\ell = \mu, e$ ]



Decay Mode	Trigger(s)	Downscaling Factor	$(N_K)$ Kaon Decays* [ $\times 10^{11}$ ]
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	Di-Muon	$\sim 2$	$7.86 \pm 0.22$
$K^+ \rightarrow \pi^- e^+ e^+$	Multi-Track + Multi-Track e	100, $\sim 8$	$2.14 \pm 0.07$

# Selection Basics

1. 3-track vertex ( $Q_{vtx} = +1$ ) in decay volume :  $(114/105 *) < Z_{vtx} < 180$  m.
2. Track momentum :  $(5/8 *) < p < 65$  GeV/c .
3. Track times consistent within  $(12/15 *)$  ns.
4.  $|p_{3trk} - p_{K^+}| < 2.5$  GeV/c .
5.  $p_T < 30$  MeV/c .
6. (Photon Vetos \*).
7. PID : MUV3 + LKr ( + RICH (for  $e^+$ ) \*).
  - Only  $\mu^\pm$  reach MUV3
  - LKr  $E/p(e) \sim 1$  ,  $E/p(\mu) \sim 0$  (MIP),  $0 < E/p(\pi) < 1$  (Hadron+EM showers)
  - RICH : ID by likelihood fit to rings ( $\pi/\mu/e$ ) [Optimized for  $\pi^+/\mu^+$  sep. for  $15 < p < 35$  GeV].

\* Differences between analyses ( $K^+ \rightarrow \pi^- \mu^+ \mu^+$  /  $K^+ \rightarrow \pi^- e^+ e^+$ ).

# $K^+ \rightarrow \pi^- \mu^+ \mu^+$ : Selection

- Use Di-Muon trigger for signal  $K^+ \rightarrow \pi^- \mu^+ \mu^+$  and normalization (SM)  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ .
- $Z_{vtx} > 114$  m: to reject upstream decays.
- $5 < p < 65$  GeV/c .
- $p_{\mu_1} < 45$  GeV/c &  $|p_{\mu_1} - p_{\mu_2}| < 35$  GeV/c : discriminate  $K_{\pi\mu\mu}$  from  $K_{3\pi}$  with decays in flight.
- 2  $\mu$  candidates hit different MUV3 tiles.
- PID :
  - $\pi$  :  $E/p < 0.85$  + 0 associated MUV3 hits.
  - $\mu$  :  $E/p < 0.20$  + an associated MUV3 hit.
- Control region (SM+LNV) :  $M_{\pi\mu\mu} < 484$  MeV/c<sup>2</sup>
- [Signal region for SM +] Blinded region (LNV) :  $484 < M_{\pi\mu\mu} < 504$  MeV/c<sup>2</sup>
- Signal region (LNV) :  $M_{\pi\mu\mu} = (493.7 \pm 3.3)$  MeV/c<sup>2</sup> [ $m_{K^+} \pm (3 \times \text{resolution})$ ]

# $K^+ \rightarrow \pi^- e^+ e^+$ : Selection

- Use Multi-Track and Multi-Track  $e$  triggers for signal  $K^+ \rightarrow \pi^- e^+ e^+$  and normalization (SM)  $K^+ \rightarrow \pi^+ e^+ e^-$ .
- $Z_{vtx} > 105$  m.
- $8 < p < 65$  GeV/c .
- LAV photon veto applied (reject Dalitz decays  $K^+ \rightarrow \pi^+ [e^+ e^- \gamma]_{\pi^0}$  and  $K^+ \rightarrow e^+ \nu_e [e^+ e^- \gamma]_{\pi^0}$ ).
- $p_\pi < 40$  GeV/c : to ensure the efficiency of the LKr20 trigger condition.
- PID :
  - $\pi$  :  $E/p < 0.85$  + 0 associated MUV3 hit.
  - $e$  :  $0.90 < E/p < 1.10$  (1 LKr cluster) + 0 associated MUV3 hit + [ $e^+$  : RICH ring fit  $e$  likelihood is highest].
- For SM selection :  $M_{ee} > 140$  MeV/c<sup>2</sup>. For LNV observe events at  $M_{ee} < 140$  MeV/c<sup>2</sup> for the first time.
- Control regions (SM+LNV) :  $M_{\pi ee} < 470$  MeV/c<sup>2</sup> &  $505 < M_{\pi ee} < 600$  MeV/c<sup>2</sup>
- [Signal region for SM +] Blinded region (LNV) :  $470 < M_{\pi\mu\mu} < 505$  MeV/c<sup>2</sup>
- Signal region (LNV) :  $M_{\pi\mu\mu} = (493.7 \pm 5.1)$  MeV/c<sup>2</sup> [ $m_{K^+} \pm (3 \times \text{resolution})$ ]